



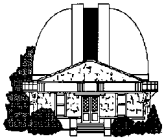
Full-sky Astrometric Mapping Explorer

<http://www.usno.navy.mil/fame>

Full-sky Astrometric Mapping Explorer

❖ **Proposed NASA Medium-Class Explorer (MIDEX)**

❖ **Joint development effort of:**



United States Naval Observatory



Naval Research Laboratory



Lockheed Martin Missiles and Space



Smithsonian Astrophysical Observatory



Infrared Processing and Analysis Center



Omitron, Incorporated

FAME Science Team

Dr. John Bahcall, Princeton

Dr. Christian DeVegt, U. Hamburg

Dr. George Gatewood, U. Pittsburg

Dr. Marvin Germain, USNO

Dr. Andrew Gould, Ohio State

Dr. Thomas P. Greene, NASA Ames

Dr. Scott Horner, USNO

Dr. John Huchra, CfA

Dr. William H. Jefferys, U. Texas

Dr. Kenneth Johnston, USNO

Dr. Barry Lasker, STScI

Dr. David Latham, CfA

Dr. David Monet, USNO

Dr. James Phillips, SAO

Dr. Robert Reasenberg, SAO

**Dr. Siegfried Roeser, Astronomisches
Rechen-Institut**

Dr. Allan Sandage, Carnegie Obs.

Dr. P. Kenneth Seidelmann, USNO

Dr. Mike Shao, JPL

Dr. Irwin I. Shapiro, CfA

Mr. Sean Urban, USNO

Dr. William Van Altena, Yale

Dr. Donald York, U. Chicago



Full-sky Astrometric Mapping Explorer

- ❖ Small satellite to perform an all sky, astrometric survey with unprecedented accuracy
 - ➔ Upgrades existing star catalogs by providing a precision catalog of 4×10^7 Stars
 - ➔ Provides positions of all bright stars ($5 < m_v < 9$) to $< 50 \mu\text{as}$
 - ➔ Provides positions of fainter stars ($9 < m_v < 15$) to $< 300 \mu\text{as}$
 - ➔ 2.5 year mission allows for accurate measurement of stellar parallax and proper motions
 - ➔ Photometric data in four Sloan DSS bands (g', r', i', z')



Full-sky Astrometric Mapping Explorer

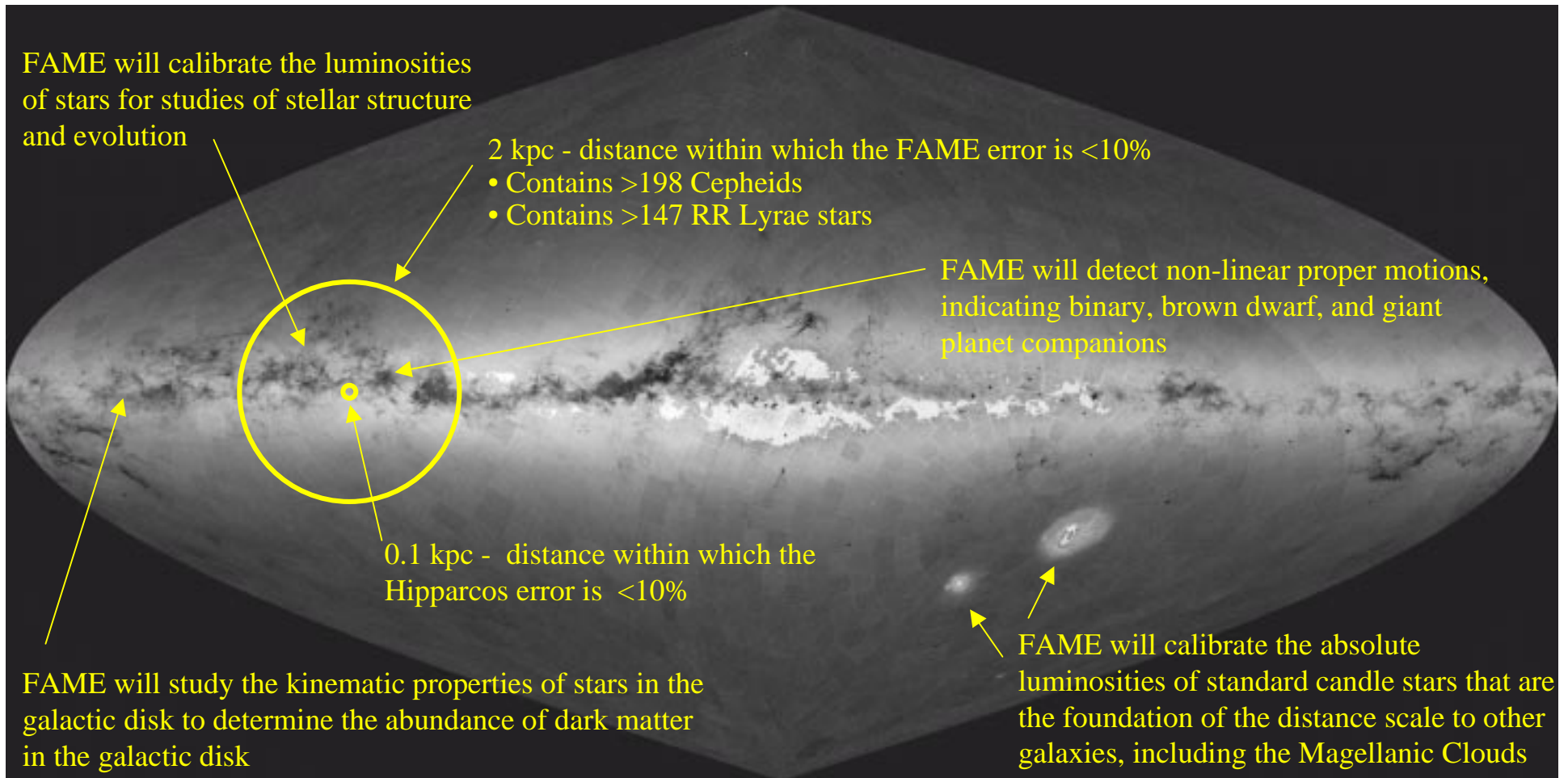
- Measure the positions, parallaxes, and four-color magnitudes of 40 million stars brighter than 15th visual magnitude
- Measure with 10% error or better the absolute trigonometric parallaxes of stars brighter than 9th visual magnitude within 2 kpc of the Sun
- Measure the positions, trigonometric parallaxes, and proper motions of all stars out to 15th visual magnitude with accuracies of:

50 μ as at 9th visual magnitude

300 μ as at 15th visual magnitude

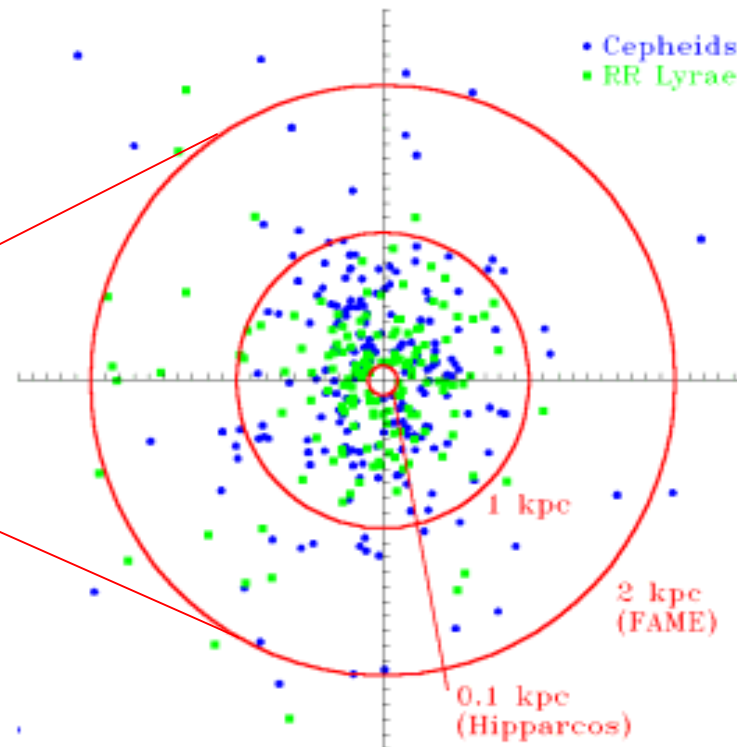
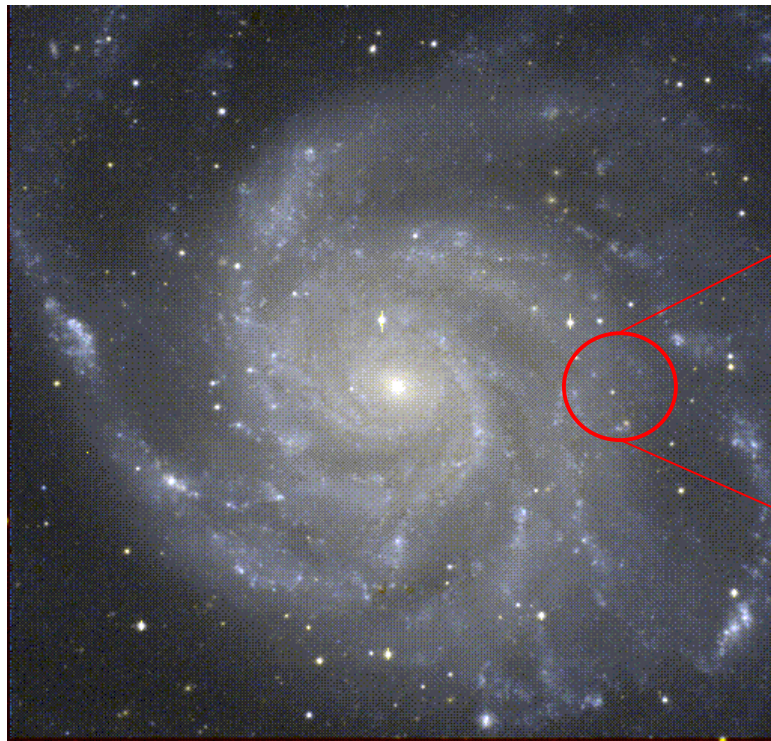


FAME Coverage of the Milky Way



FAME Science - FAME will map our quadrant of the galaxy out to 2 kpc from the Sun providing the information needed to calibrate the standard candles that define the extragalactic distance scale, calibrate the absolute luminosities of stars of all spectral types for studies of stellar structure and evolution, and detect orbital motions caused by brown dwarfs and giant planets. FAME will not only improve on the accuracies of star positions determined by Hipparcos but also expand the volume of space for which accurate positions are known by a factor of 8,000.

FAME Coverage of the Milky-Way

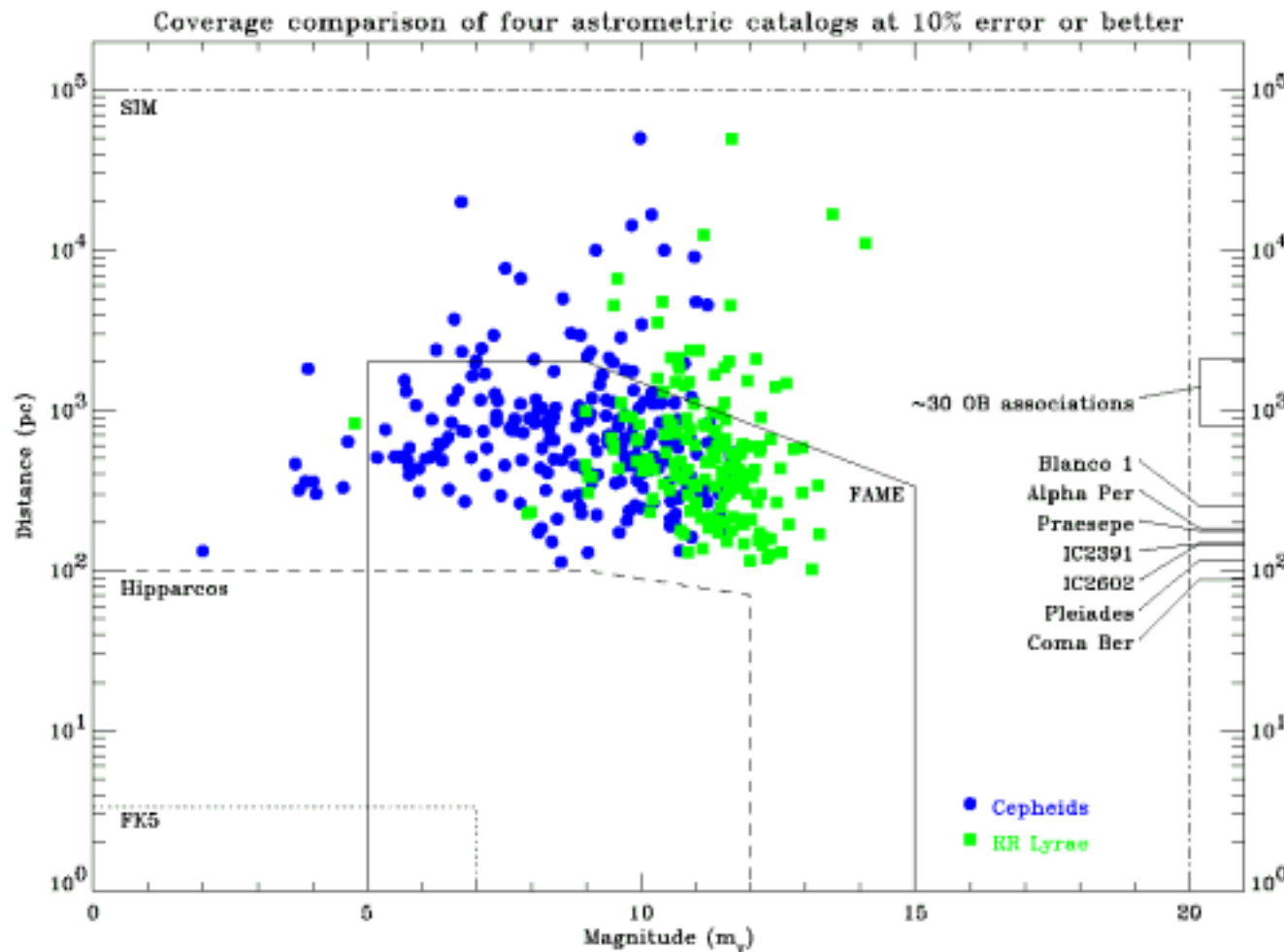


Foundation of the Extragalactic Distance Scale

- ❖ **FAME parallax observations will accurately determine the distances to the nearest “standard candle” stars**
 - ↳ Cepheid variables - luminosity related to period
 - ↳ RR Lyrae stars
- ❖ **Determining the distance to nearby Cepheids and RR Lyrae stars is fundamental in defining the distance scale to nearby galaxies and clusters of galaxies**



FAME Distance/Magnitude Limits and Standard Candle Stars



FAME observations of standard candle stars - For standard candle stars to serve as the foundation of the extragalactic distance scale, distances to the nearby stars need to be accurately determined. Hipparcos did not determine distances to these stars with a high level of accuracy. FAME is designed to determine distances accurate to 10% error or better to a large sample of Cepheids and RR Lyrae stars, thus refining the extragalactic distance scale. While SIM may obtain distances to some of these stars to better accuracy, SIM is a pointed mission that will only determine distances for a small number of known standard candle stars.



Cluster Cepheid Variables

STAR	Period		Distance	
	(day)	<V>	(kpc)	SNR
SU Cas	1.95	5.97	0.26	76
SZ Tau	4.03	6.53	0.59	34
U Sgr	6.74	6.70	0.63	32
V Cen	5.49	6.82	0.67	30
S Nor	9.75	6.42	0.91	22
T Mon	27.02	6.13	1.67	12
H0144972	5.10	8.87	1.69	12
CPD-537400	11.22	8.37	1.69	12
RZ Vel	20.40	7.09	1.72	12
WZ Sgr	21.83	8.03	1.75	11
DL Cas	8.00	8.97	1.79	12
RS Pup	41.39	7.01	1.79	11
RU Sct	19.70	9.40	2.04	10
VY Car	18.93	7.46	2.08	10



Field Cepheid Variables

Within 1 kpc

STAR	Period		Distance	
	(day)	<V>	(kpc)	SNR
DT Cyg	2.50	5.78	0.45	44
FF Aql	4.47	5.38	0.45	44
BG Cru	3.34	5.47	0.45	44
RT Aur	3.72	5.42	0.50	40
Y Sgr	5.77	5.75	0.59	34
T Vul	4.43	5.75	0.63	32
V1334 Cyg	3.33	5.85	0.67	30
AH Vel	4.23	5.68	0.67	30
AX Cir	5.27	5.85	0.71	28
IR Cep	2.11	8.60	0.71	28
R Tra	3.39	6.66	0.71	28
U Aql	7.03	6.47	0.77	26
MY Pup	5.70	5.65	0.77	26
U Vul	8.00	7.14	0.77	26
EW Sct	10.00	8.01	0.77	26
S Cru	4.69	6.57	0.83	24
S Sge	8.37	5.66	0.83	24
Y Oph	17.14	6.15	0.53	24
BF Oph	4.06	7.28	0.91	22
V Cen	5.49	6.82	0.91	22
T Cru	6.73	6.59	0.91	22
TU Cas	9.14	7.65	0.91	22
V636 Sco	6.79	6.66	0.91	22
BB Sgr	6.64	6.99	1.00	20
EU Tau	2.10	8.15	1.00	20
RV Sco	5.47	7.05	1.00	20



RR Lyrae Stars with Parallax Measurement Errors < 10%

STAR	Period		Distance	
	(day)	<V>	(kpc)	SNR
RR Lyr	3.69	8.57	0.25	80
XZ Cet	2.83	9.20	0.38	52
CS Eri	2.05	9.20	0.48	42
MT Tel	2.07	9.28	0.48	42
AE Boo		10.00	0.56	26
UV Oct	3.49	9.79	0.56	27
V429 Ori	3.17	10.00	0.59	24
DH Peg	1.80	9.78	0.63	23
XZ Cyg	2.93	10.53	0.63	16
RR Cet	3.57	10.33	0.63	18
X Ari	4.48	10.48	0.63	16
RZ Cep	2.04	10.31	0.63	18
RX Eri	3.86	10.10	0.67	20
VX Sci		10.50	0.67	15
SU Dra	4.58	10.24	0.67	18
TU Uma	3.61	10.24	0.67	18
SW And	2.77	10.76	0.67	12
V Ind	3.02	10.48	0.71	14
TT Lyn	3.96	10.17	0.71	18
DX Del	2.97	10.26	0.71	16
SV Eri	5.17	10.23	0.71	16
DN Aqr	4.31	10.50	0.71	14



Stellar Evolution

- ❖ **Calibrate the absolute luminosities of solar neighborhood stars**
 - ↳ Population I
 - ↳ Population II
- ❖ **Enable diverse studies of stellar and galactic evolution**
- ❖ **Determine distances and ages of galactic globular clusters using the determined absolute luminosities**
- ❖ **Determine ages of extragalactic globular clusters**
- ❖ **Resolve the discrepancy in distances to the Pleiades and other open clusters**

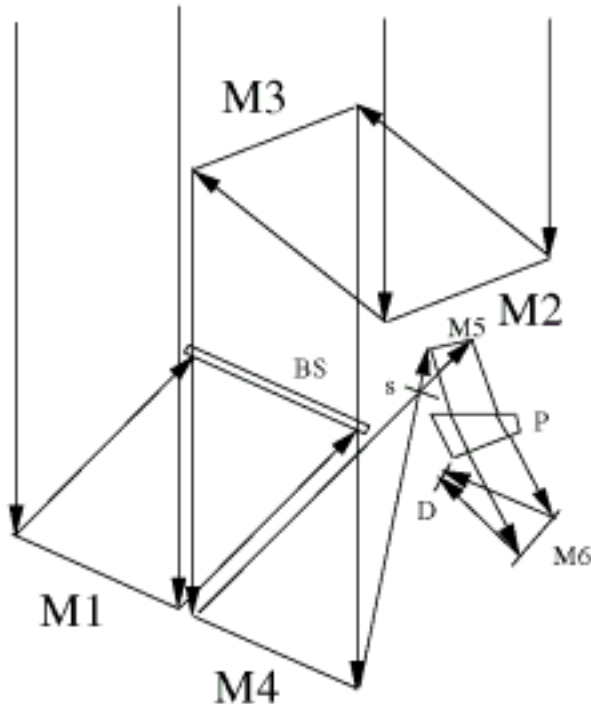


Stellar Companions

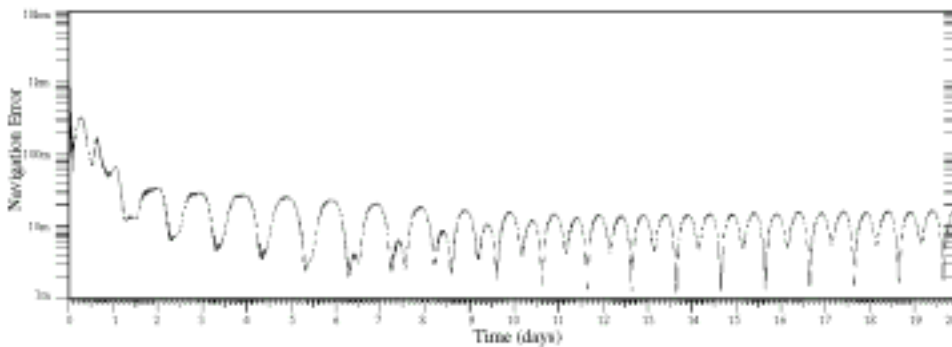
- ❖ Determine the inclinations and thus the masses of known exoplanets detected by radial velocity techniques
- ❖ Determine the frequency of solar-type stars orbited by brown dwarf companions in the mass range of 10 to 80 M_{jup} with orbital periods up to twice the duration of the FAME mission
- ❖ Explore the transition region between brown dwarfs and giant planets, which appears to be in the range of 10 to 30 M_{jup}



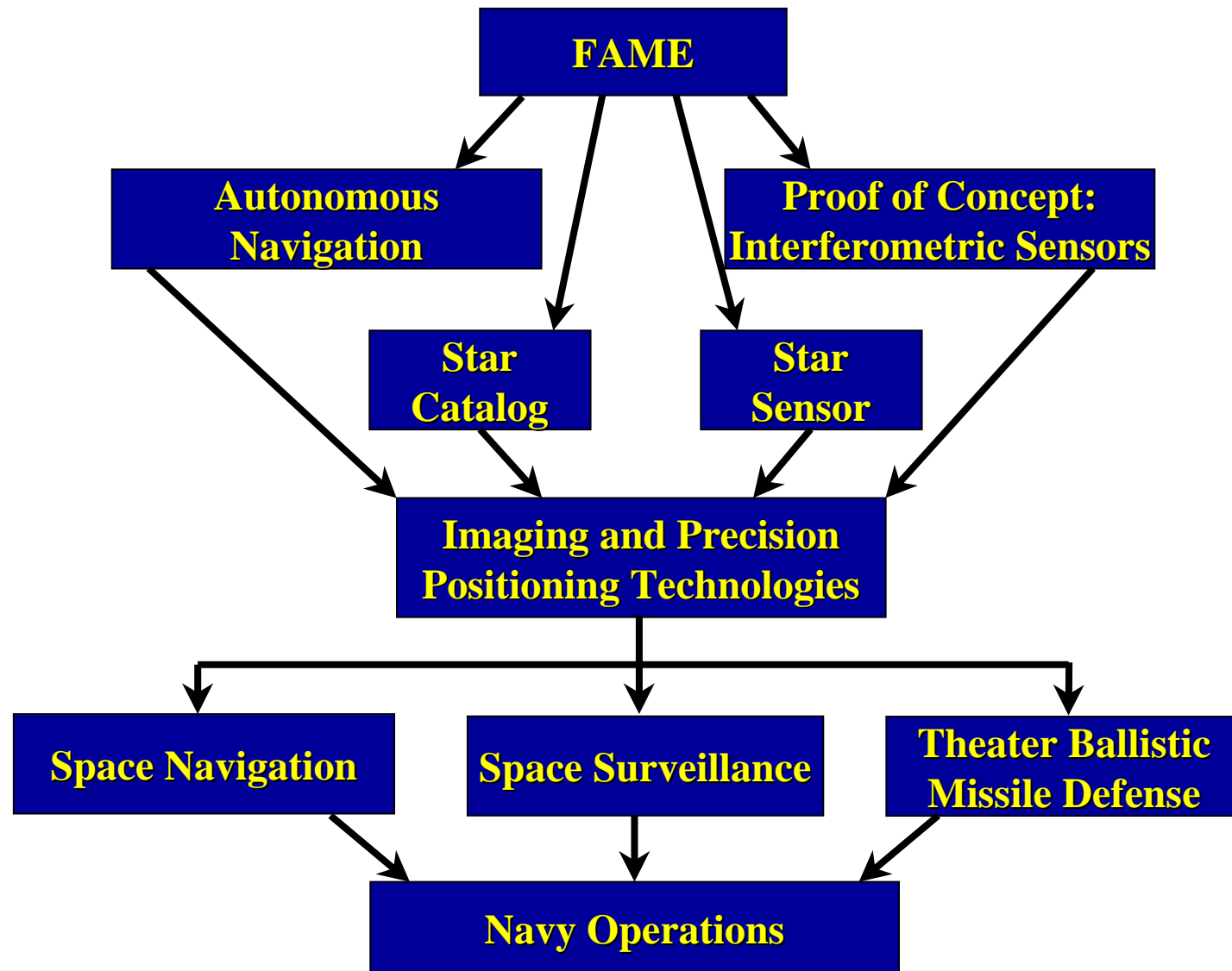
Space Navigation Concept



- ❖ Precise stellar positions enable space navigation at meter accuracy
- ❖ Similar to inertial navigation unit (INU) but based on stellar inertial reference frame
- ❖ Stellar aberration determine position
- ❖ Proposed design
 - ➔ < 40 kg
 - ➔ < 130 W
 - ➔ Monolithic ULE Glass construction
 - ➔ 1028x1028 CCD Array
- ❖ Simulation demonstrates 10 meter resolution assuming 10 sec updates and 20 μ s accurate star map.



FAME Technology/Data Transition Paths



High Accuracy Astrometry *DoD Relevance (1 of 2)*

❖ Precise inertial reference frame

➡ Astrometry and reference frame maintenance are Navy (USNO) mission

➡ Astrometric requirements currently met by Hipparcos astrometric satellite data 1991.25

- Degrades with time due to proper motion inaccuracies
- In 2010 current requirements no longer met

❖ FAME provides 0.000050 arcsecond precision for short term needs

❖ FAME provides 0.00010 arcsecond precision over long term to meet current and future needs



High Accuracy Astrometry

DoD Relevance (2 of 2)

❖ **Develop optical interferometry in space**

- ➔ **FAME serves as pathfinder for Optical Interferometry (OI) in space**
 - Characterize materials and techniques for OI
 - Precursor for NASA, future NASA astrometry missions (SIM, TPF)
 - Precursor for space based imaging missions
- ➔ **Develop technology for inertial orientation and navigation using only stellar data**
 - Precursor for future high precision star trackers
 - Navigation by stars only, 1.0m precision in space

❖ **Fundamental astronomy and astrophysics**

- ➔ **Stellar distances, parallaxes, proper motions**
- ➔ **Planetary information**
- ➔ **Galactic structure, rotation, cosmic distance scale**



Example: Theater Ballistic Missile Defense

- ❖ **FAME supports theater ballistic missile defense by providing real time wide area surveillance and target recognition for queuing AEGIS, to enable rapid target acquisition with minimum system configuration, by providing precise data for predicting target trajectory**
 - ➔ **Down looking high flyer**
 - Interferometric multispectral sensor developed for FAME
 - Precision orbit and attitude data (based on FAME catalog) for precision geolocation
 - ➔ **Limb looking low flyer**
 - Interferometric multispectral sensor developed for FAME
 - FAME stellar catalog for precise tracking



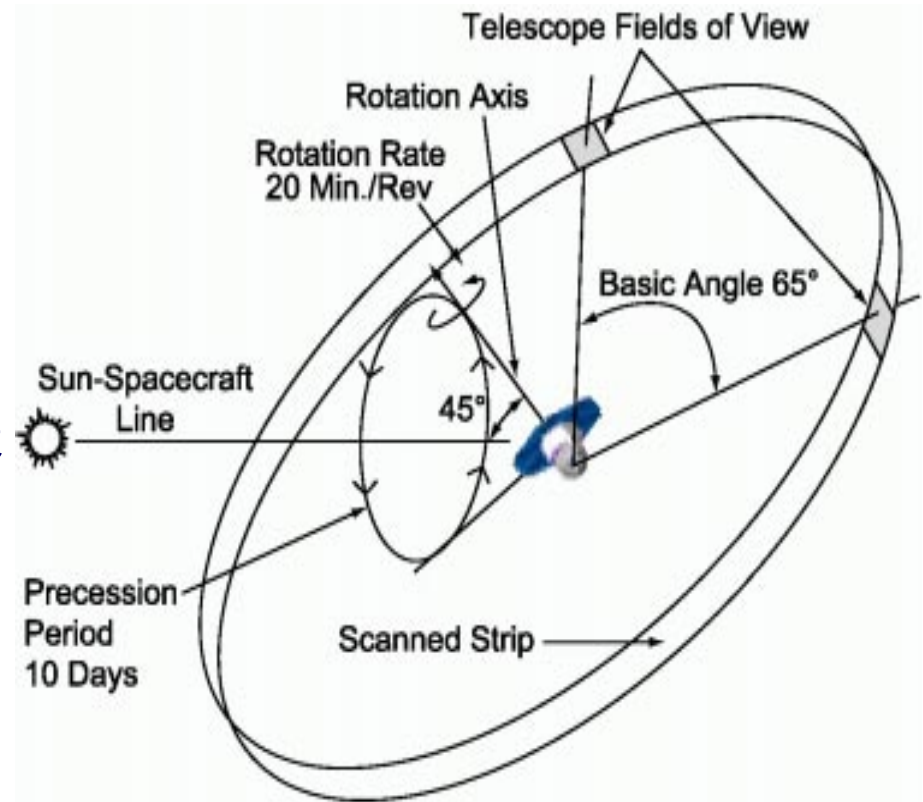
Reference Frames

- ❖ Fundamental frame based on extragalactic radio sources ~0.2 mas accuracy
- ❖ Optical reference frame
 - ➔ Based on Hipparcos ~1 mas in 1991
 - ➔ Tied to radio frame ~0.6 mas in 1991
 - ➔ Degrades with time
 - ➔ Accuracy depends on magnitude
 - ➔ Possible rotation with respect to fundamental
- ❖ Dynamical reference frame
 - ➔ Based on solar system
 - ➔ Ephemerides dependent
 - ➔ Inner & outer solar systems different
- ❖ Terrestrial reference system
 - ➔ Based on Geoid
- ❖ Determination of all frames and links from U.S. Naval Observatory



FAME Mission Description

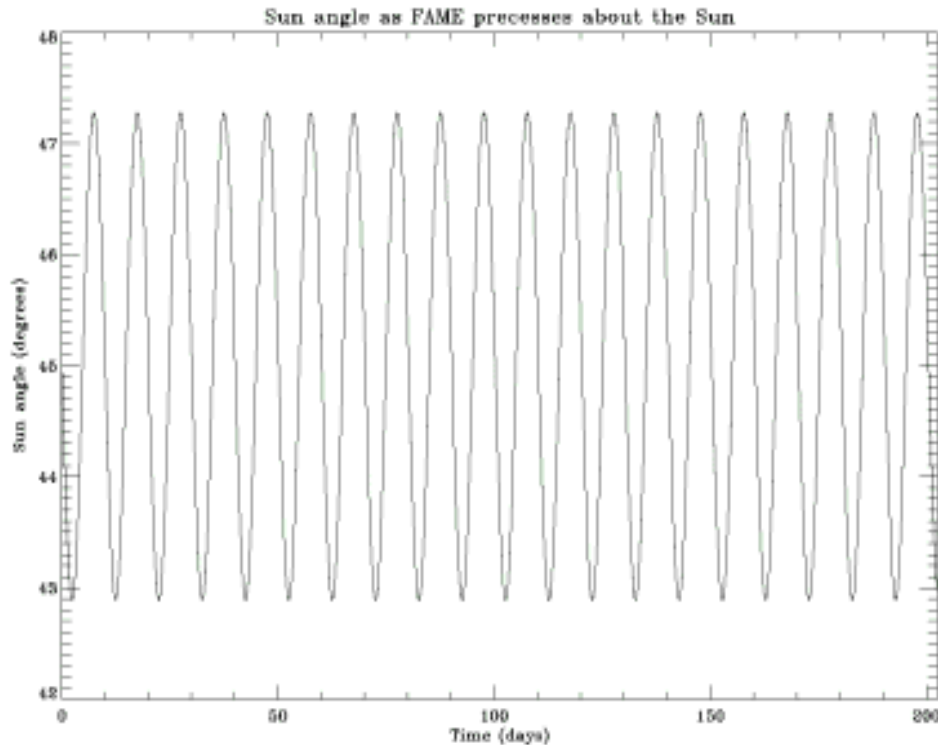
- ❖ The telescope has two fields-of-view separated by a 65° basic angle
- ❖ The spacecraft will rotate with a 20 minute period with the apertures sweeping out a great circle on the sky
- ❖ The spacecraft rotation axis is at a 45° angle to the Sun
- ❖ The solar radiation pressure on the solar shield results in precession about the Sun-spacecraft line with a 10 day period



The FAME observing concept - The axis of the FAME spacecraft is pointed 45° from the Sun and precesses around the Sun with a 10 day period. The FAME spacecraft rotates with a 20 minute period. The two fields of view are normal to the rotation axis and are separated by a 65° degree basic angle.



Solar Radiation Precession



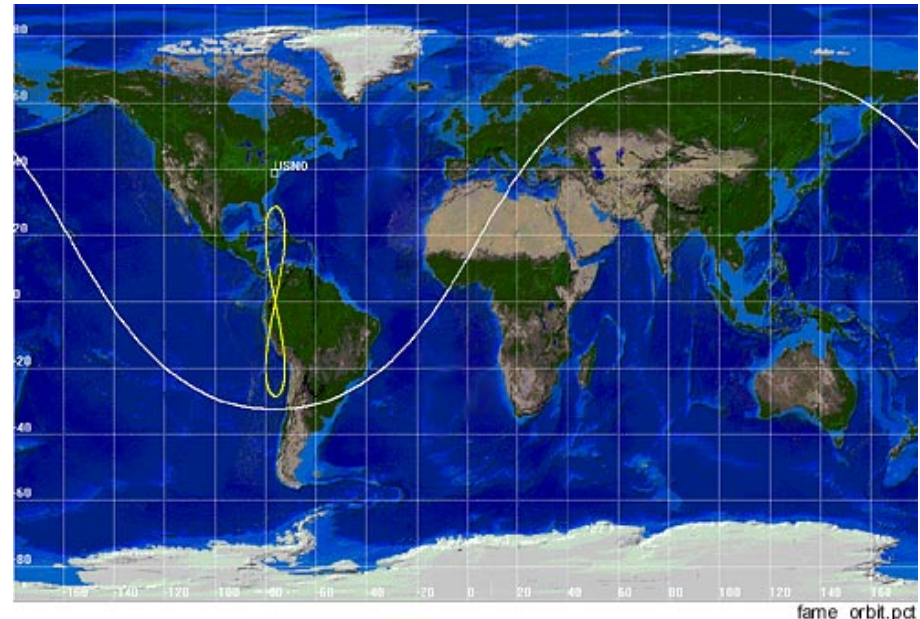
Model of FAME precession - This shows the results of a model of the FAME precession from solar radiation pressure on the Sun shield. The Sun angle varies from the nominal 45° by a few degrees but does not have a linear drift towards or away from the Sun.

- ❖ Deployed Sun shield is slightly swept back and acts as a solar sail
- ❖ Solar radiation pressure on the Sun shield produces a torque that move the spin axis
- ❖ Sweep of shield is adjusted at deployment to tune the precession rate
- ❖ This results in smooth precession (thruster firings are rare) resulting in long periods of coherent rotation



FAME Mission Description

- ❖ All-sky coverage enabled by Spacecraft Motion
- ❖ Spacecraft and Instrument have no mechanisms or moving parts after deployment
- ❖ FAME will be in geosynchronous orbit so it will be in continuous contact with the ground station

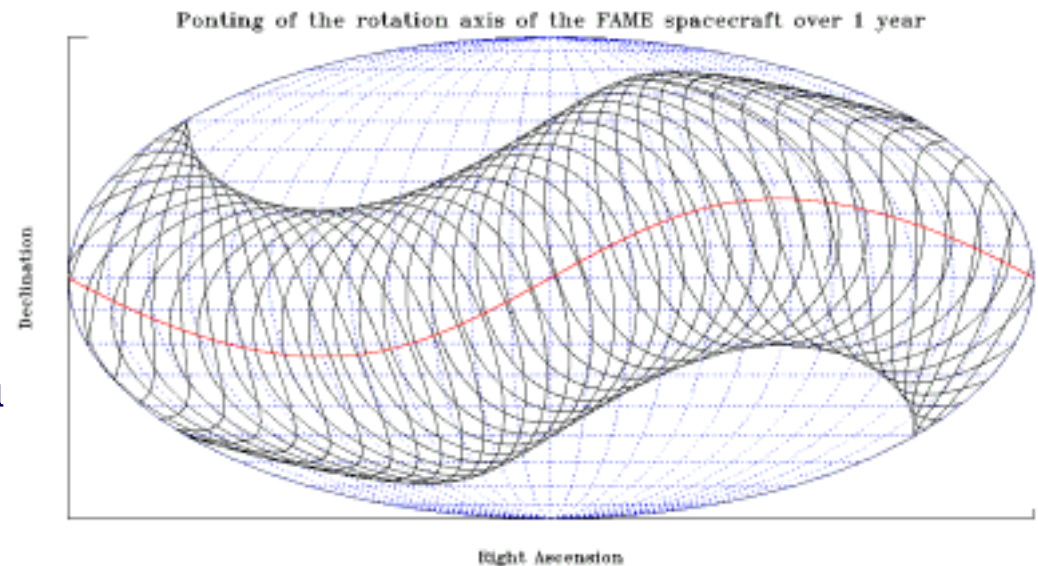


The FAME orbit - The yellow line is a possible geosynchronous orbit of FAME with a 28.7° degree inclination. The white line shows the area at geosynchronous altitude visible from Washington, D.C. A geosynchronous orbit was selected to allow continuous contact with the spacecraft due to the high data rate of FAME.



FAME Mission Description

- ❖ Solar radiation pressure on the Sun shield produces a torque that precesses the spacecraft rotation axis
- ❖ This results in smooth precession resulting in long periods of coherent rotation
- ❖ The spacecraft rotation and precession, along with the orbit of Earth around the Sun, combine to give complete sky coverage over the course of 3 months

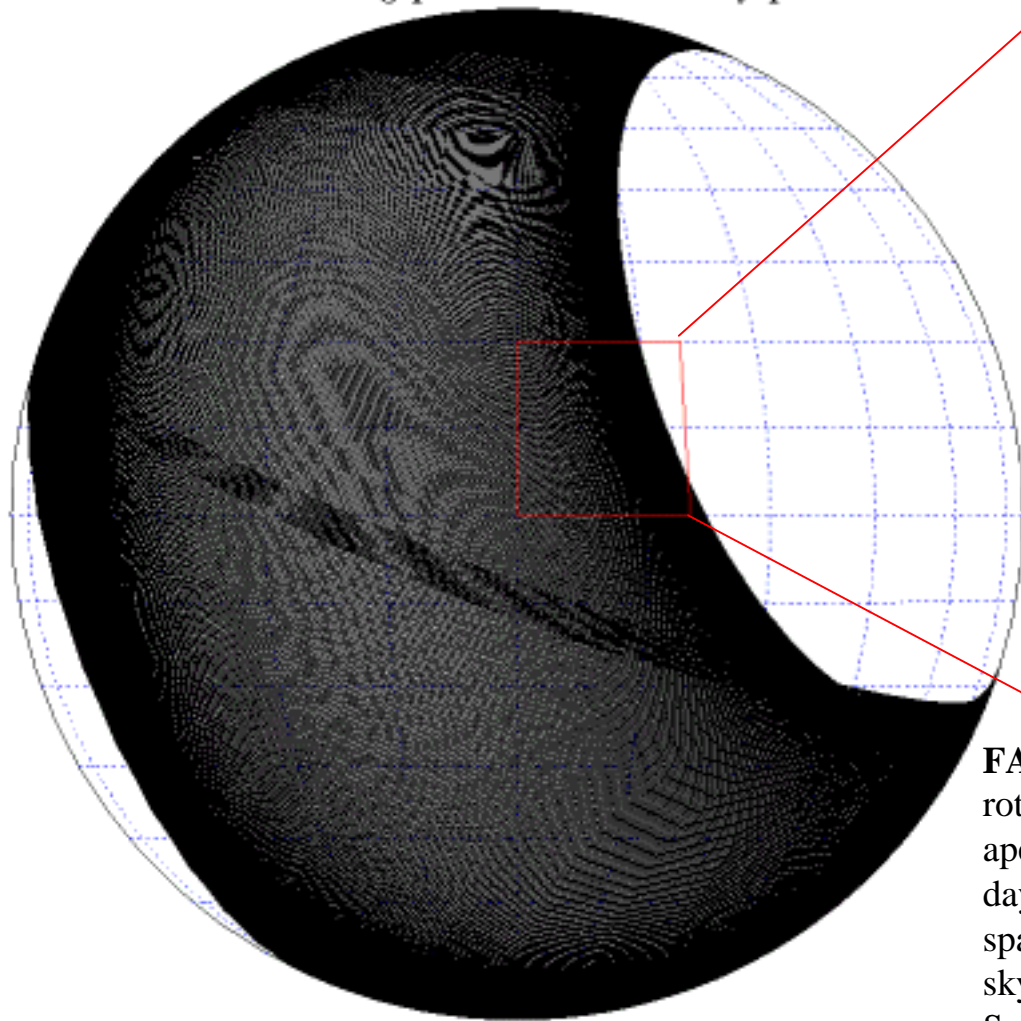


Pointing of FAME rotation axis - The spacecraft rotation axis precesses about the Sun with a 10 day period and a nominal Sun angle of 45° . Thus, every 10 days FAME covers the entire sky except for exclusion zones within 45° of the Sun and the anti-Sun direction.

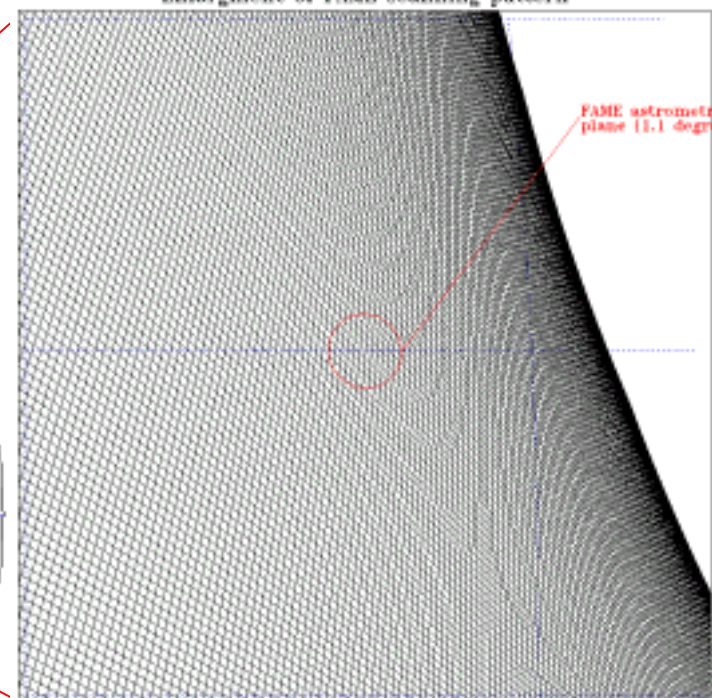


FAME Scan Pattern

FAME scanning pattern over a 10 day period



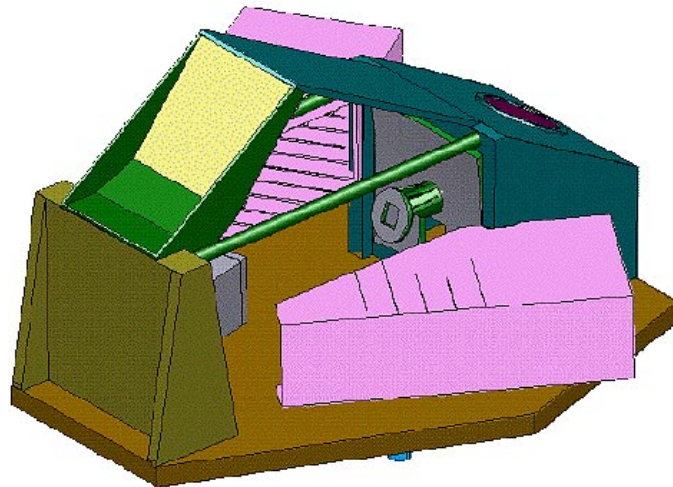
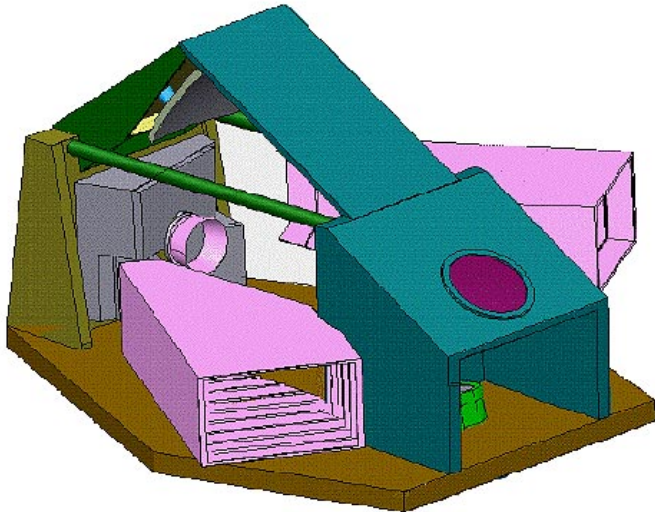
Enlargement of FAME scanning pattern



FAME scan pattern - The FAME spacecraft rotates with a 20 minute period scanning the two apertures across a great circle on the sky. The 10 day precession of the spacecraft about the Sun-spacecraft line results in FAME covering the entire sky except for exclusion zones within 45° of the Sun and the anti-Sun direction every 10 days.



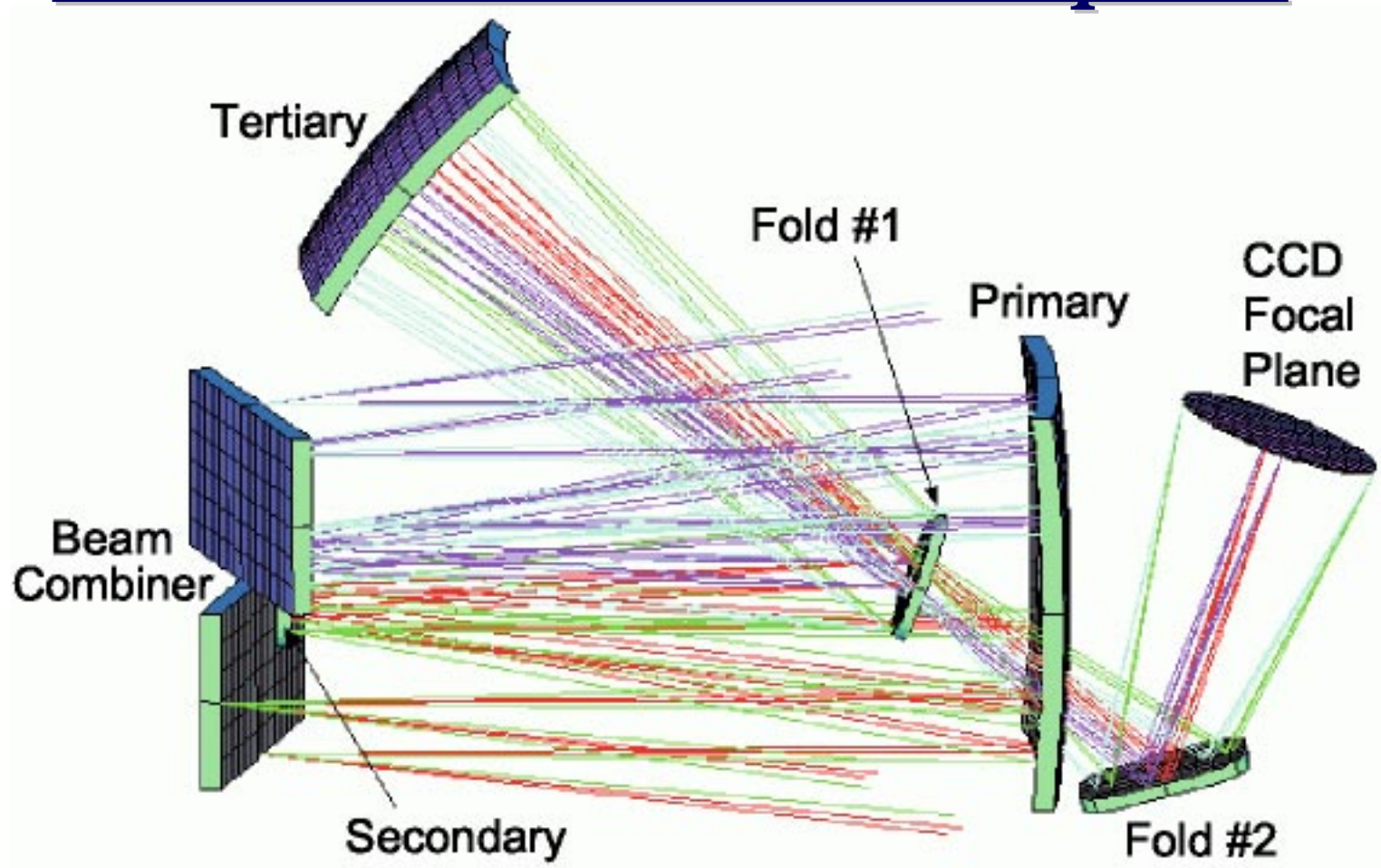
FAME Instrument Description



- ❖ Instrument developed by Lockheed Martin
- ❖ Total weight 165 kg
- ❖ Total power 250 W
- ❖ Instrument optics
 - Two input apertures
 - 50 × 25 cm aperture size (each)
 - 400 to 900 nm spectral range
- ❖ Back illuminated CCDs



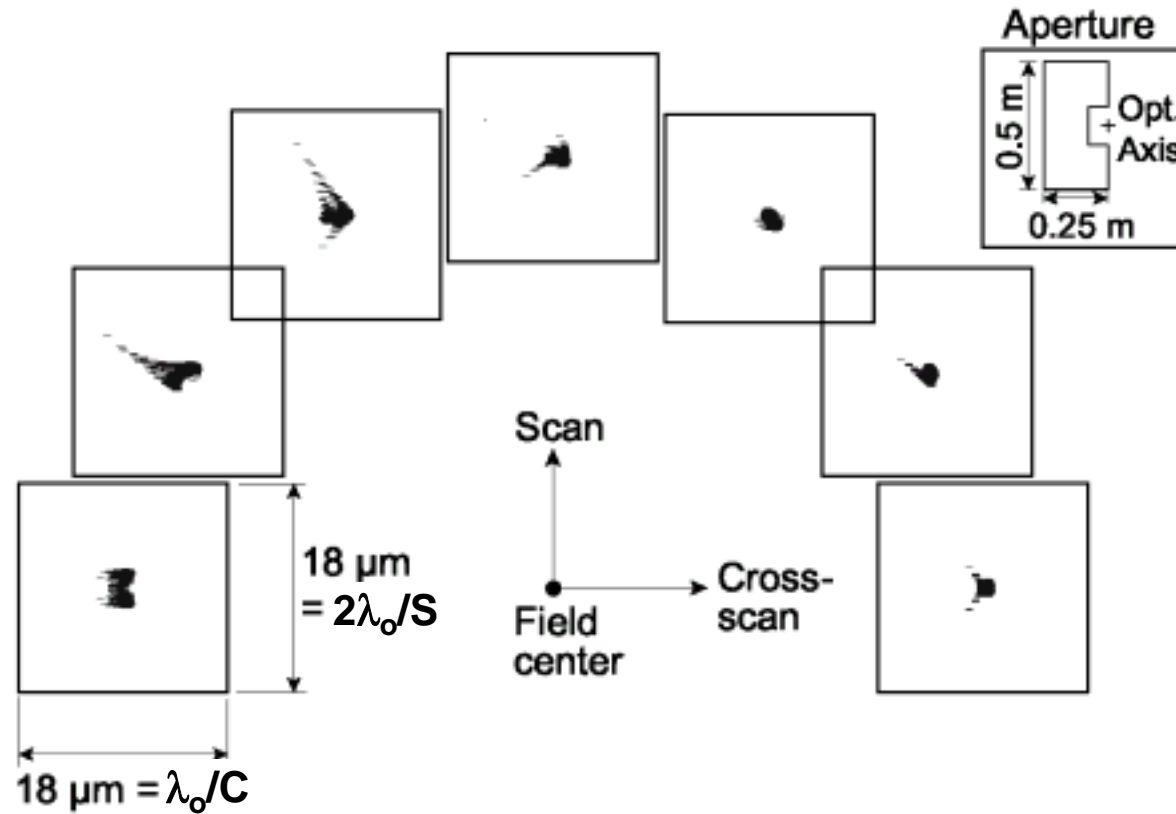
FAME Instrument Description



FAME optical ray-trace diagram - The beam combiner gives the primary two fields of view, each with 50 × 25 cm apertures. The fields of view are separated by 65° on the sky. The two fields are then superimposed on the focal plane.



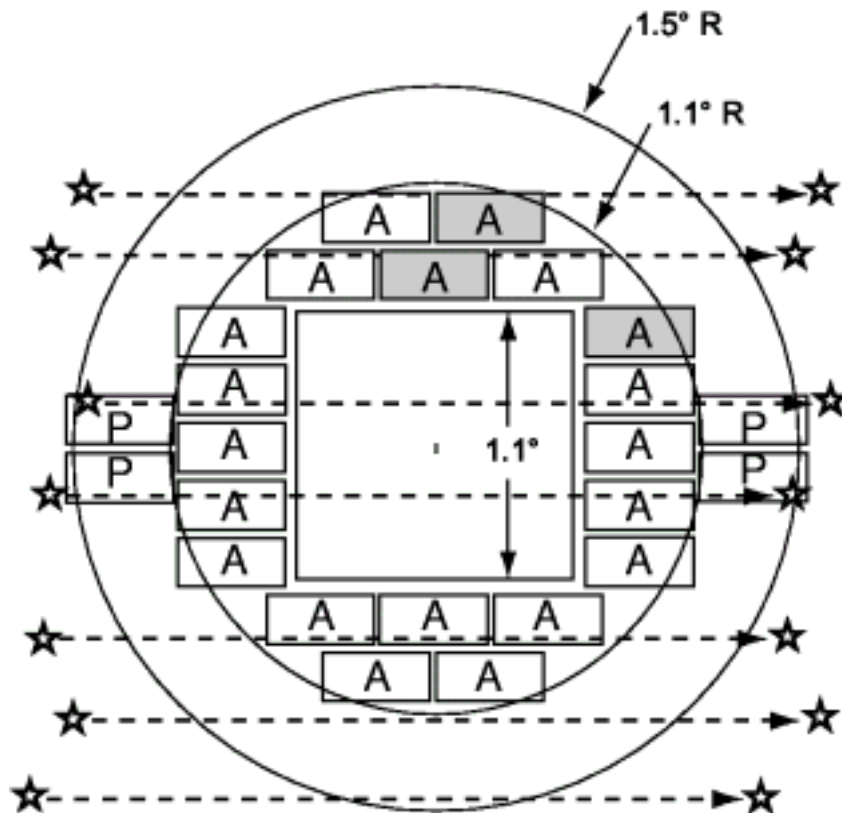
Optical Performance



The FAME spot diagram - The optical spot diagram for points along an arc at a field angle of 1.03° from the optical axis.



FAME Instrument Description



The FAME focal plane - 24 2k×4k CCDs arranged around a 1.1° radius from the center of the field of view. Devices marked with 'P' are the 4 photometric CCDs and devices marked with 'A' are the 20 astrometric CCDs. The 3 'gray' devices have neutral density filters for astrometry of brighter stars.

❖ Telescope produces images of Stars using 24 large format CCDs

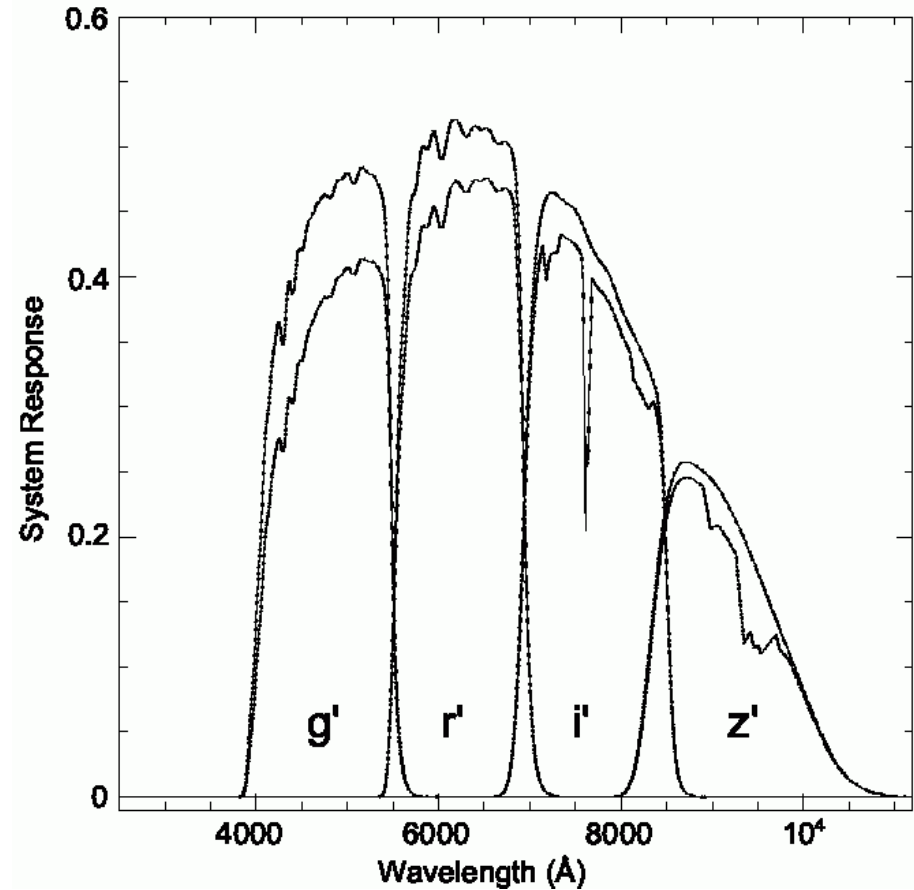
- ➔ Images of stars are continually traversing CCD array as the spacecraft rotates
- ➔ CCDs use time delay integration
- ➔ Synchronization of CCD clock rate and image motion is assured via rotation rate sensors
- ➔ Star images are time tagged, windowed, and transmitted to Earth.
- ➔ 3 CCDs are covered by neutral density filters for astrometry of bright stars



FAME Instrument Description

(continued)

- ❖ For Photometry, four of the CCDs are covered by Sloan filters for photometry
- ❖ The g', r', i', and z' SDSS bands are used
- ❖ Each of the four photometric CCDs are covered by 2 filters (each filter covers half of the CCD columns)



FAME Error Sources

CCD characteristics

read noise

dark current

non-linearity

charge transfer inefficiency

**deterioration of CTE from radiation
damage**

variations in the CCD flatness

pixel-to-pixel gain variations

sub-pixel gain variations

wavelength dependent gain variations

CCD defects

CCD pixel registration errors

**color dependent penetration of
photons**

recovery from saturation

CCD clock cross-talk

CTE behind bright stars

ADC errors



FAME Error Sources

(continued)

Instrument alignment

point-spread function (PSF)

PSF variations with position in field

**misalignment of the CCD column
with the rotation**

variation of plate scale across field

Instrument stability

PSF variations with time

**errors in CCD clock rate
relative to rotation**

**error in determination of
rotation rate**

error in setting the clock speed

Variations in telescope structure

thermal

evaporation

Variation in basic angle



FAME Error Sources

(continued)

Photon statistics

Spacecraft

CCD/window contamination

**aberration due to error in knowledge
of S/C velocity**

Stellar/External

saturation

stellar activity

stellar companions

incorrect stellar model

confusion

cosmic rays

scattered light



Fame Error Sources

- ❖ **CCD characteristics**
 - Read noise, QE variation, etc.
- ❖ **Instrument alignment**
 - PSF variations
- ❖ **Instrument stability**
 - Thermal effects
- ❖ **Spacecraft**
 - Knowledge of spacecraft velocity
- ❖ **Stellar/external**
 - Photon statistics



FRAME Estimated Error Budget

Error Source	Error (μ as) a priori	Error (μ as) a posteriori
Photon Statistics		
$m_V=9$	540	540
$m_V=15$	10800	10800
Read Noise ($7e^-$ rms, $m_V=9$)	6600	6600
QE Variation	560	<10
λ-dependent absorption in CCD	300	30
Charge transfer effects	800	80
Incorrect Stellar Spectrum Model	4000	50
Undetected Companions	60	60
Onboard clock error	<100	<1
Telescope geometry variations	100	<10
Optical Distortion	2000	20
Refraction in CCD window	1	<1
Rotation Rate Changes	10^6	25
Ephemeris (1cm/sec knowledge)	7	<1



FAME Estimated Error

Budget Totals

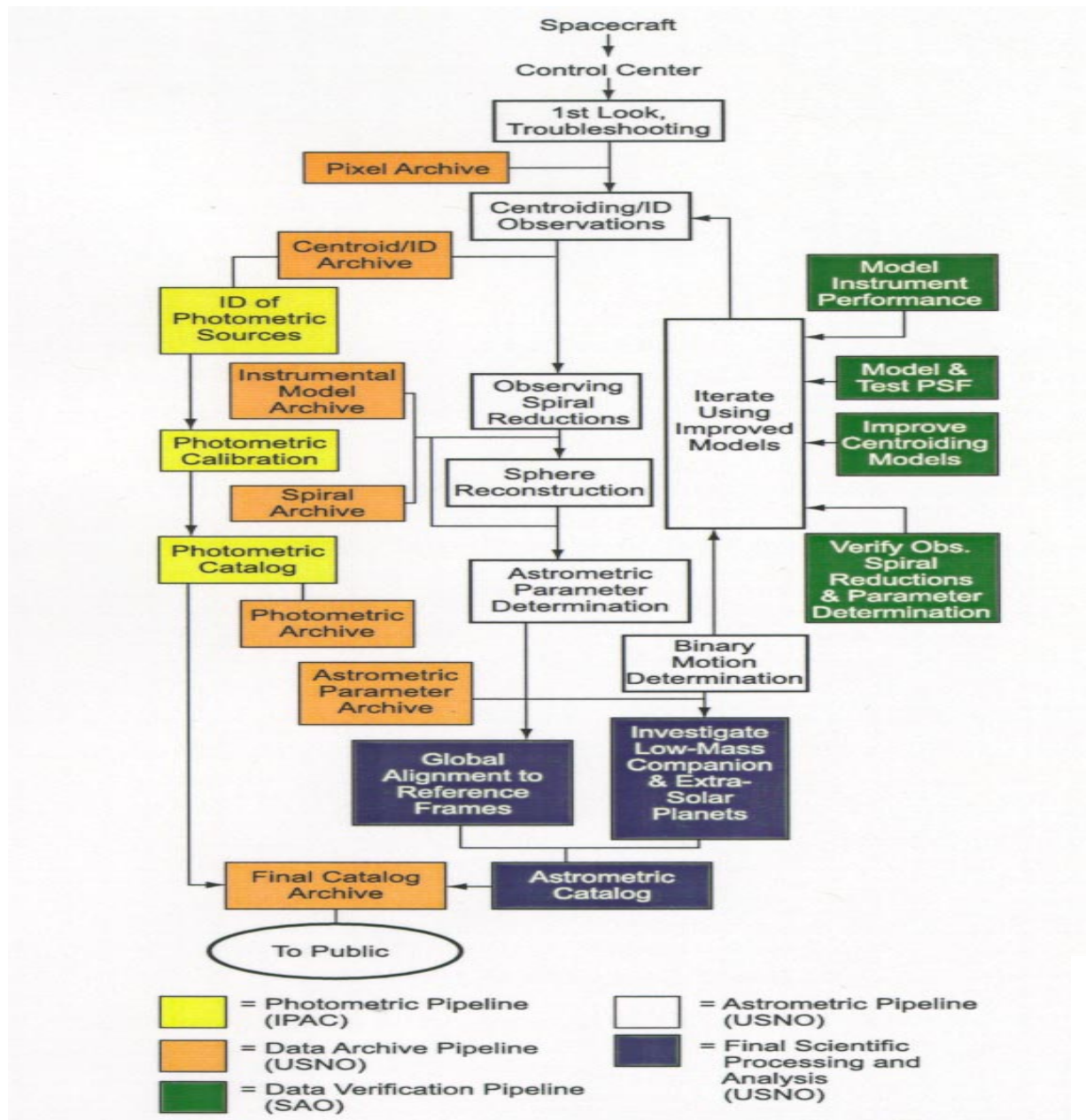
Visual Magnitude (m_v)	ND Filter Accuracy* (μas)	Gated Array Accuracy* (μas)
5	29	14
7	48	14
9	15	14
11	30	28
13	76	70
15	226	208

***Assumes systematic error contribution is 10 μ as**

The FAME accuracy - The predicted accuracy of FAME as a function of visual magnitude (m_v). The second column shows the accuracy if neutral density filters over 3 of the astrometric CCDs are used for astrometry of the brighter stars (baseline design). The third column shows the accuracy if the CCDs are only integrating during part of the time when a bright star is traversing the device (alternate design).



FAME Data Reduction and Analysis

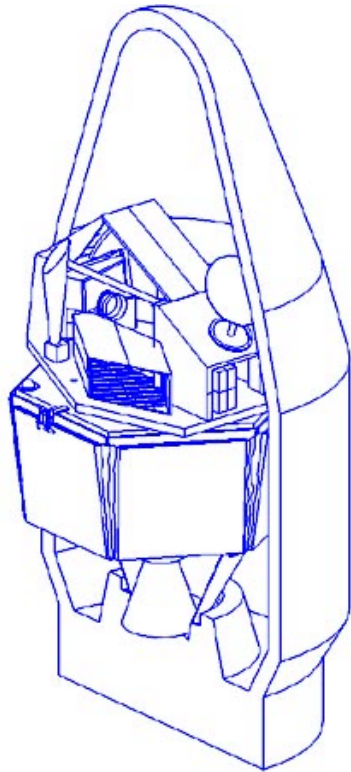


Program Philosophy

- ❖ Solve for parameters over entire data set
- ❖ Push errors to limit
- ❖ Must evaluate
 - ↳ Simulations
 - ↳ Experiments



FAME Spacecraft Bus Description

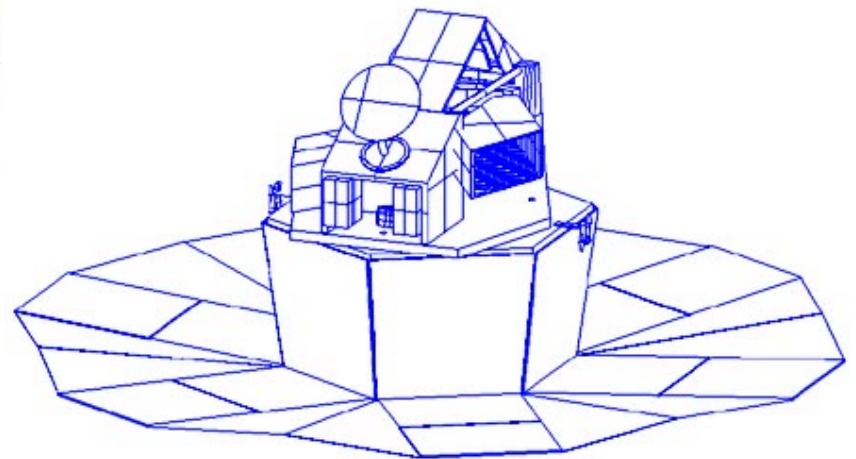


**Spacecraft in Delta II
2.9m fairing**



**Spacecraft before solar
shield deployment
(cutaway)**

**Instrument cover removed
for clarity in all views**

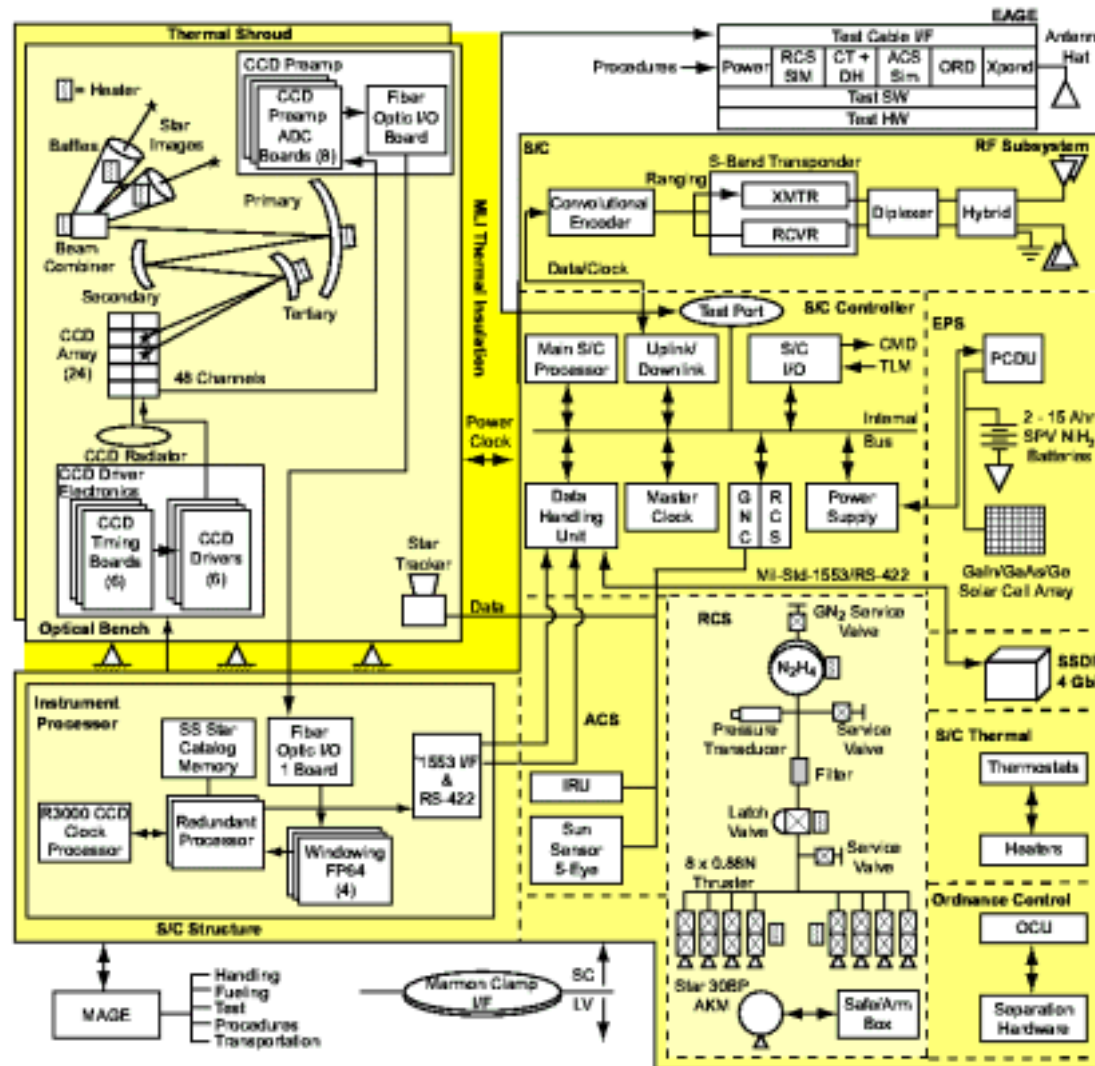


On orbit configuration

❖Spacecraft design uses component heritage from Clementine



FAME Spacecraft Block Diagram



The FAME spacecraft and instrument block diagram - The instrument blocks are on the left side of the figure and the spacecraft blocks are on the right.



FAME Technology Challenges

- ❖ Centroiding accuracy of CCD in time delay integration to 1/700 pixel
- ❖ Solar radiation attitude control without thrusters
- ❖ Thermal stability of 1 mK for optical bench
- ❖ Communications link to support data downlink of 400 kbps continuous
- ❖ Microarcsecond astrometric data reduction to model all effects including aberration, relativistic effects, geodesic precession, and nutation



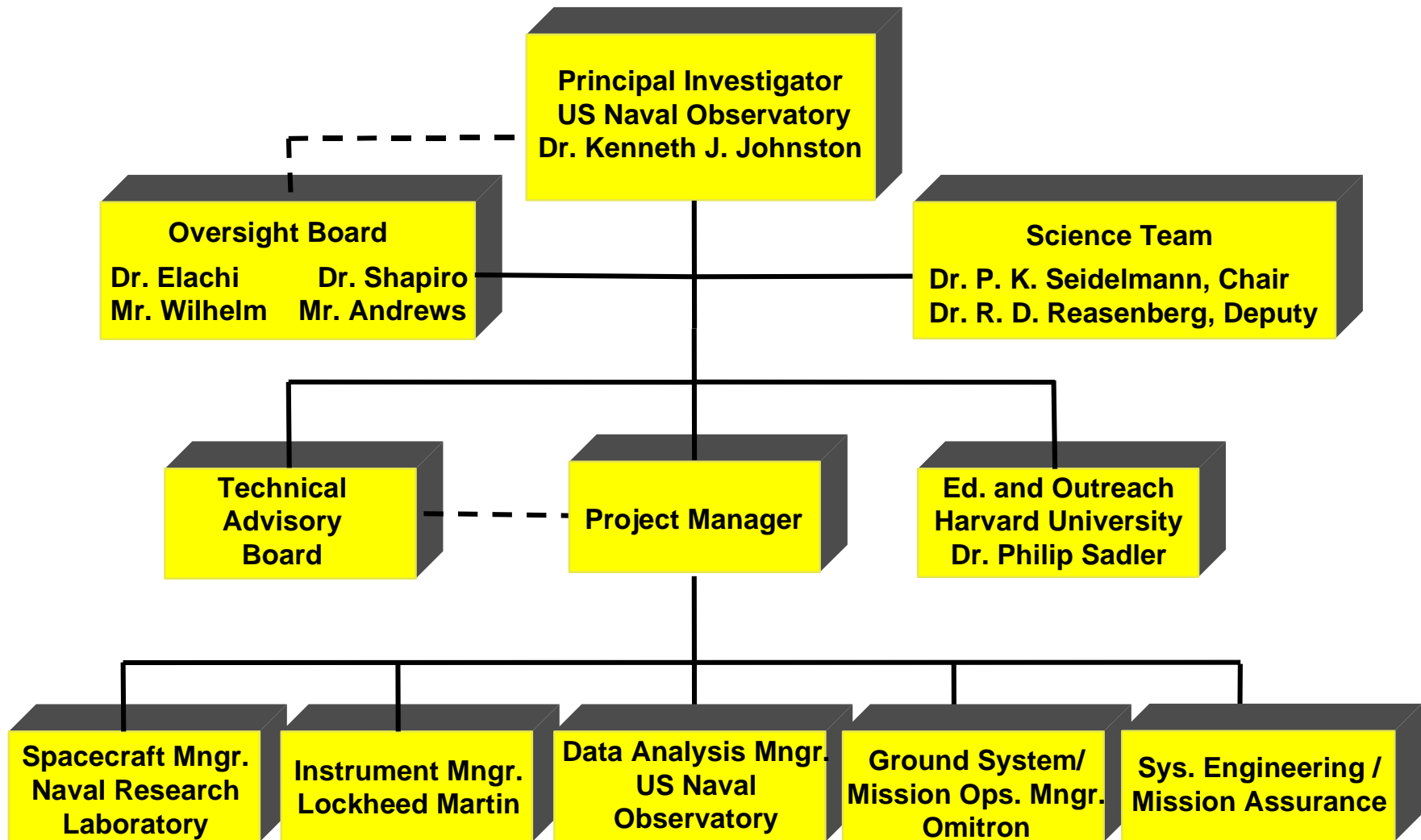
FAME Technology Challenges

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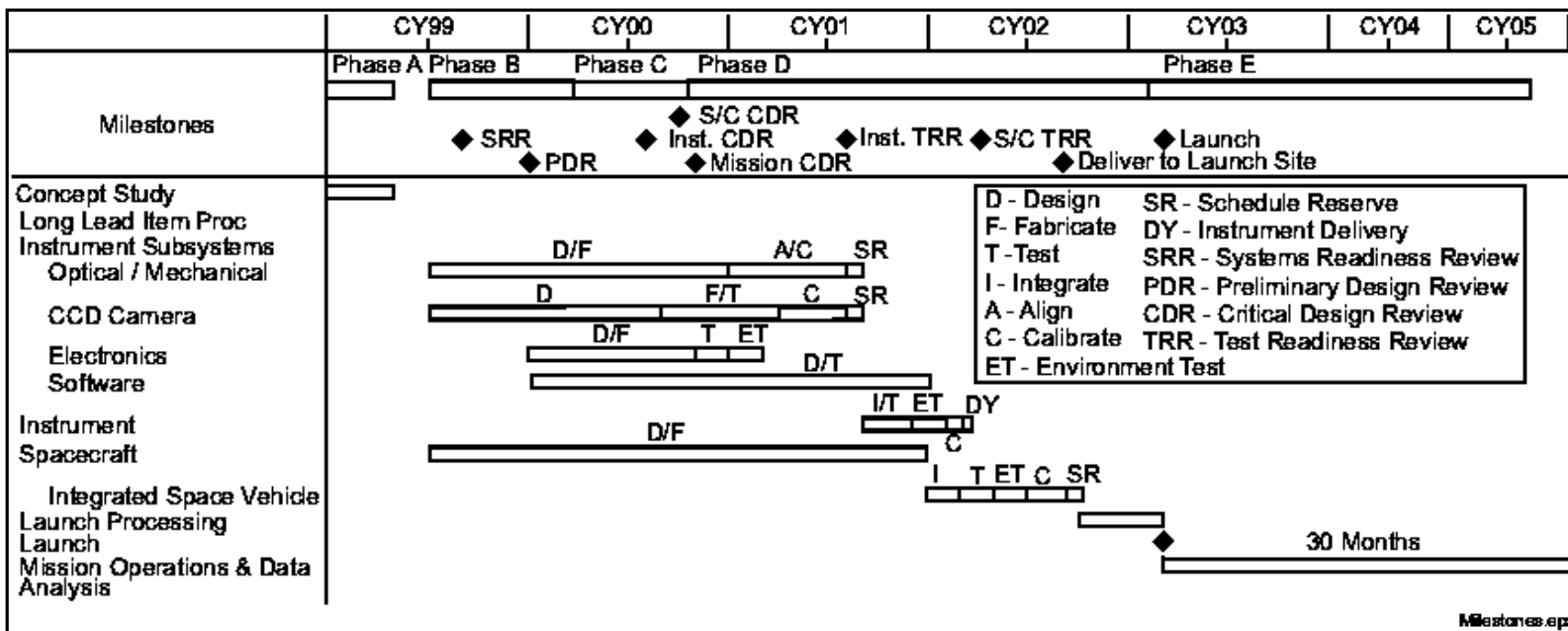
- ❖ Large number of large format CCDs in the radiation environment at geosynchronous orbit
- ❖ Data solution for 40,000,000 stars with 4000 observations each for position, parallax, proper motion, and non-linear motions
- ❖ Total astrometric errors at 15 microarcseconds before photon statistics
- ❖ Optimum readout, on board processing, storing, tagging of data, transmission, and solutions



FAME Organization



FAME Schedule



Phase A January - April 1999

Phase B June 1999 - February 2000

Phase C March - October 2000

Phase D November 2000 - February 2003

Launch March 2003

NASA mission to October 2005

Possible DoD extended mission to 2008



FAME Summary

Spacecraft, Launcher, and Orbit	
Launcher (to GTO, 28.7 degree inclination)	Delta 7425
Launch capability at GEO	1132 kg
Apogee Kick Motor	Star 30BP
Orbit	Geosynchronous (GEO) 35786 km
Instrument Mass	165 kg
Total Spacecraft mass and Contingency w/AKM	961.6 kg
Mission Lifetime	2.5 years
Instrument	
Effective Focal Length	7.5 m
Number of Apertures	2
Aperture Size	0.50m x 0.25m, each
Primary Mirror Size	0.56m x 0.56m
Focal Plane Scale	0.0275 arc-sec/micron
Airy box size at nominal wavelength (600nm)	0.5 arc-sec (1.2 pixels)
CCD Size	2048 x 4096 pixels
Pixel Size	15 microns
Pixel on Sky	0.413 arc-sec
Rotation Period	20 minutes
Precession Period	10 days
Rotation Rate	2618 CCD rows/sec; 0.382 msec per row
Time for star to traverse a CCD	1.56 sec
No. of amplifiers per CCD	2
Mean angle between Sun and spin axis	45 degrees
Drift of star due to precession	< 4 pixels/CCD crossing
CCD Binning	1 x 5
CCD readout rate per amp after binning	536 kHz
Number of Astrometric CCDs, Total	20
Number of Astrometric CCDs with Neutral Density Filters	3
Number of Photometric CCDs	4
Photometric Bands	Sloan g', r', i', z'
ADC	3 at 12 bit (staggered)
No. of times a star is observed (astrometric)	4000
No. of times a star is observed (photometric)	1080
Instrument Performance	
Wavelength Range	400 to 900 nm
Magnitude Range (mv)	5 - 15
Astrometric Accuracy (positions and parallaxes in μ as; proper motions in μ as/yr.)	50 for $V < 9$, 300 for $V < 15$
Photometric Accuracy	1 millimagnitude



Summary

- ❖ **FAME has been proposed as a NASA MIDEX mission to determine accurate positions, parallaxes, and proper motions for 40 million stars**
- ❖ **Recalibrates the extragalactic distance scale**
- ❖ **Determines absolute luminosities of a wide range of spectral types**
- ❖ **Detects companion stars, brown dwarfs, and giant planets**
- ❖ **Enables studies of the kinematics of our galaxy**
- ❖ **Defines an optical reference frame for future scientific, commercial, and military endeavors**

